High Density Thermal Energy Storage with Supercritical Fluids (SuperTES)

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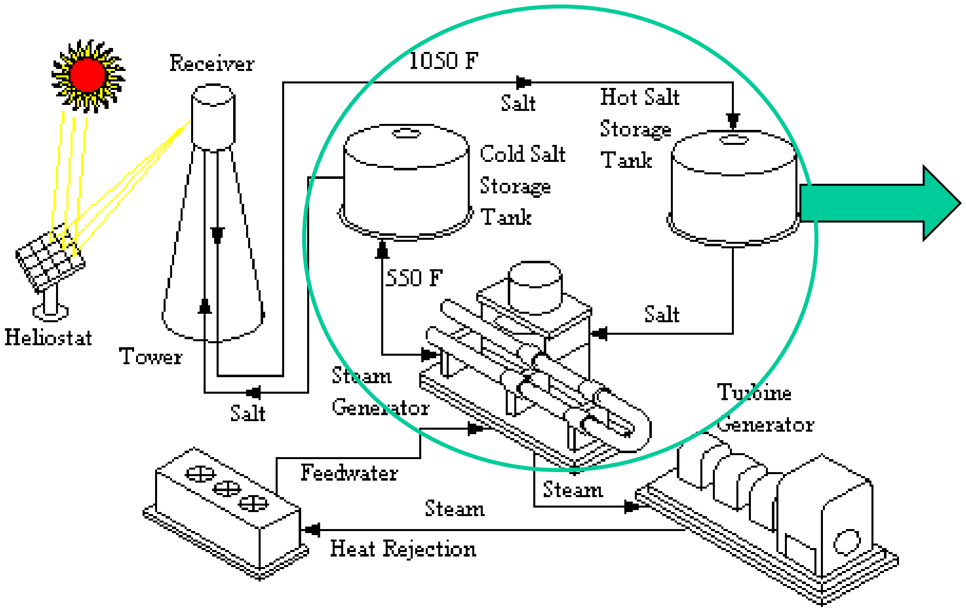
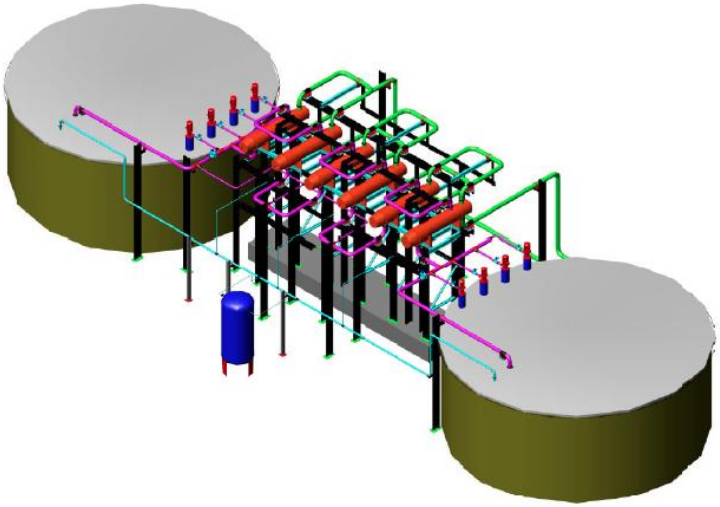
Overview

- A novel high-energy density, low-cost thermal energy storage concept using supercritical fluids
  - Enhanced penetration of solar thermal for baseload power
  - Waste heat capture
- Paper presents feasibility looking at thermodynamics of supercritical state, fluid and storage system costs
- System trades
  - comparing the costs of using supercritical fluids vs molten salt systems in utility-scale applications

Solar Thermal Plant with Storage





Ref: "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts" NREL/SR-550-34440 (2003) by Sargent and Lundy LLC Consulting Group

ARPA-E Funded Project

- ARPA-E's transformational technologies call
- Proposed key novel aspects:
  - Supercritical storage allowing significantly higher storage densities
  - Modular and single-tank (vs two-tank as for molten salt)
    - Internal heat exchangers (minimized heat loss)

- Strong team led by UCLA (Dr. Wirz) covering breadth of TRLs
  - UCLA : Low-TRL (fluid chemistry, system studies and build support)
  - JPL: Mid TRL (thermal, fluids, structural, tank design and build)
  - SoCalGas: High TRL (field demo)
  - Vendors: Chromasun (provider of solar panels)

- Prototype and field demonstrations

Project Objectives

- Three primary goals:
  - Demonstrate a cost-effective thermal energy storage (TES) concept for high temperature applications
  - Develop a modular single-tank TES design
  - Demonstrate a 30 kWh TES

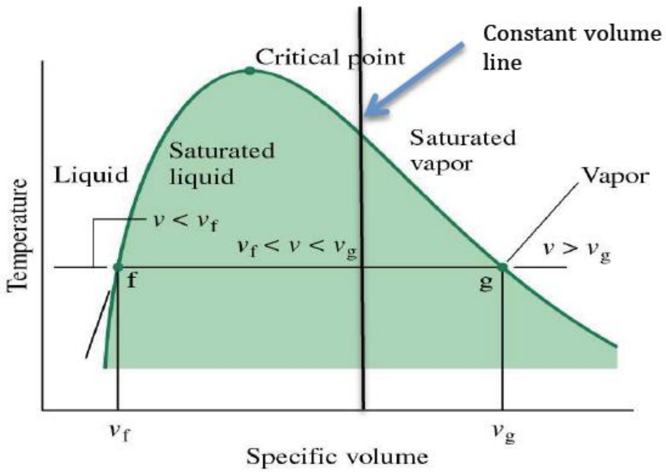
- Goals will be accomplished in 2 phases (Top level)
  - Phase 1 activities (Concept development):
    - Fluid selection
    - System analysis
    - Development and testing with a small (5 kWh/66L) tank
  - Phase 2 activities (Scale-up):
    - Development of prototype (10 kWh/133L) tank
    - Performance characterization of micro-CSP with and without TES at JPL site
    - Development of full-scale (30 kWh/400L) tank for field integration at SoCalGas site

Thermal Energy Storage SOA

- Current sensible heat technologies
  - two-tank direct,
  - two-tank indirect,
  - single-tank thermocline
  - storage media such as concrete, castable ceramics rely on sensible heat
- PCM explored in 80's by DOE
  - Abandoned due to complexities, life
- In 2008 restarted funding TES and HTF
  - Mostly sensible heat related
  - Or didn't address costs $/kWh
- ARPE-E's new program "High Energy Advanced Thermal Storage"

Supercritical Storage

- Supercritical operation permits capturing and utilizing heat taking advantage of latent and sensible heat, both in the two-phase regime as well as in supercritical regime while at the same time, reducing the required volume by taking advantage of the high compressibilities



- Storage performance and pressures can be optimized by judicious selection of fluid with the following key properties
  - High Latent Heat of Vaporization, ΔH_{vap}
  - High specific heat, C_p (C_v)
  - High T_c, T_b
  - Low vapor pressure

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Initial Fluid Comparisons

JPL

Moderate Temperature Application (T_{cold} = 373K, DT = 100K)			
	Specific Storage (kJ/kg)	Volumetric Storage Capacity (kJ/m^3) (vapor press at 200 ^{o}C)	\$/kWh (\$/kg)
Compressed water	418	362,000 (15 atm)	Negligible
Therminol (VP-1)	229	228,700 (<1 atm)	78 (\$5/kg)
Fluid1	241	303,850 (<1 atm)	8 (\$0.55/kg)
Fluid2	200	216,609 (<1 atm)	16 (\$1/kg)
High Temperature Application (T_{cold} = 563K, DT = 100K)			
Supercritical Fluid1	*720*	*324,741 (66 atm, z = 0.25)*	*2.75 (\$0.55/kg)*
Supercritical Fluid2	*541*	*387,122 (66 atm, z = 0.219)*	*6.50 (\$1.00/kg)*
Molten Salt ($NaNO_3$, KNO_3)	145	129,860 (2 tanks)	25 – 50 (\$1-\$2/kg)

- 400 organic fluids evaluated based on thermodynamics alone
- Factor of 10 cost reductions on fluids for high temperature applications possible

Modeling Approach

- Departure functions used with Peng Robinson (P-R) EOS to determine state changes in enthalpy for fluid

$$A - A^0 = -\int_{\infty}^{V} (P - \frac{RT}{V}) dV + RT \ln \frac{V}{V^0}$$

Helmoltz Departure Function

$$S - S^0 = \frac{\partial}{\partial T}(A - A^0) = \int_{\infty}^{V} \left[\left(\frac{\partial P}{\partial V} \right)_V - \frac{R}{V} \right] dV + R \ln \frac{V}{V^0}$$

Entropy Departure Function

$$H - H^0 = (A - A^0) + T(S - S^0) + RT(Z - 1)$$

Enthalpy Departure Function

$$H[T_2,P_2] - H[T_1,P_1] = \left(H[T_2,P_2] - H^0[T_2,P_0]\right) + \left(H^0[T_2,P_0] - H^0[T_1,P_0]\right) + \left(H^0[T_1,P_0] - H^1[T_1,P_1]\right)$$

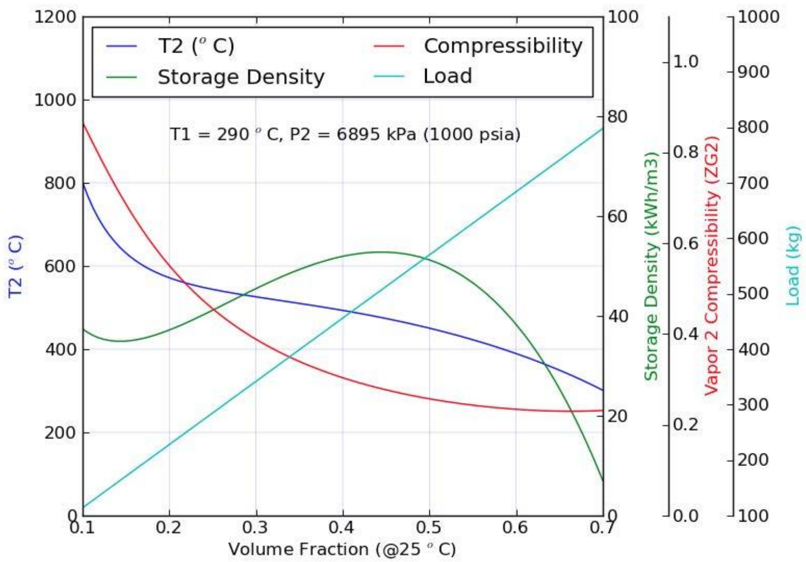
Enthalpy Change between States 1 & 2

- End state pressures and temperature determine the tube wall thickness
- Fixed end temperature chosen not to exceed 500 °C as allowable stress drops significantly beyond this temperature

System Cost Approach

- Fluid enthalpy changes with fixed volume
  - Fluid cost $/kWh based on fluid cost $/kg and loading
  - Tank material cost $/kWh based on tube mass which is driven by fluid pressure
- Peng-Robinson equation of state using P_c, T_c, ω
- Heat transfer effects from HTF to tube negligible
- Analysis assumed Stainless Steel TP 316 for its corrosion resistance
  - Optimal tube wall thickness for different pressure ratings conforming to ASTM A213, ASTM A249 or ASTM 269 respectively

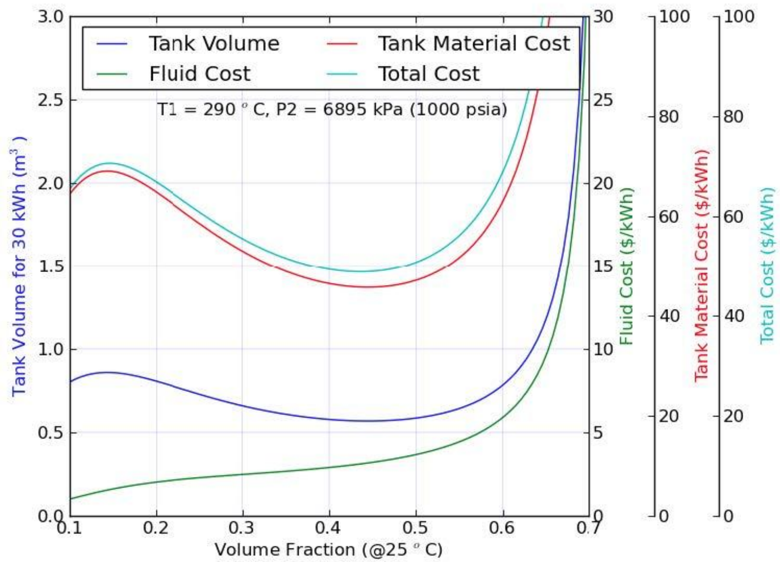
Modeling Results - Thermo



Sample result for P_2 = 6.985 MPa (1000 psia)

- Initial temp (T_1 = 290 °C, P_1 = 413 kPa) for all cases
- 4 final pressure (P_2)cases
  - 4.2MPa (609 psia)
  - 6.895 MPa (1000 psia)
  - 10.342 MPa (1500 psia)
  - 13.789 MPa (2000 psia)
- As loading (volume fraction) increases in 1m^3 tank
  - Storage density [green] goes through peak
  - Final temperatures, T2 [blue] comes down from 800 °C @ fixed P_2
  - Compressibility, z, [red] changes from near ideal gas to highly non-ideal

Modeling Results – System Costs



Sample result for P_2 = 6.985 MPa (1000 psia)

- Pressure rating derived from Lame formula with 130 MPa (18.8 kpi) allowable stress and 4:1 FS
  - Derating of 0.6 assumed for 400°C $<T_2<$ 500°C
    - Example for 500 °C, P_2= 6.895 MPa [1000 psia] need to spec tube dia for 11.49 MPa [1666 psia]
      - Need thickness > 2.36E-3 m [0.093"] for 5.08E-2 m [2"] tube OD
- Total cost goes through a minimum at ~45% fill fraction
  - Minimum cost for given final fill conditions is ~$55/kWh
  - Fluid cost [green] is small fraction of total cost [cyan]

Summary of Optimal Costs

- Optimal cost results for 4 final pressure cases when T2 <= 500 °C

P_2 (psia)	T_2 (°C)	Storage Density (kWh/m³)	Load (kg/m³)	Fluid Cost ($/kWh$_t$)	Tank Cost ($/kWh$_t$)	Total Cost ($/kWh$_t$)	Salt Cost ($/kWh$_t$) (@$2/kg)
609	461	70.0	460	2.17	23.02	25.19	29.30
1000	498	84.8	439	1.71	28.43	30.14	24.91
1500	492	99.4	535.5	1.78	37.52	39.3	22.19
2000	499.6	112	570	1.68	44.88	46.57	22.18

- Results indicate that though storage density increases as P2 is allowed to go higher, the penalty is higher cost as cost of metal starts making an impact
- For the lowest cost case, cost of salt alone exceeds cost of supercritical naphthalene + tank material cost
  - Assumptions
    - Bulk cost of naphthalene = $0.36/kg
    - Bulk cost of eutectic salt (KNO3+NaNO3) = $2/kg
    - Bulk cost of SS 316H (alibaba.com) = $1.40/kg

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Cost Comparisons for Utility-Scale

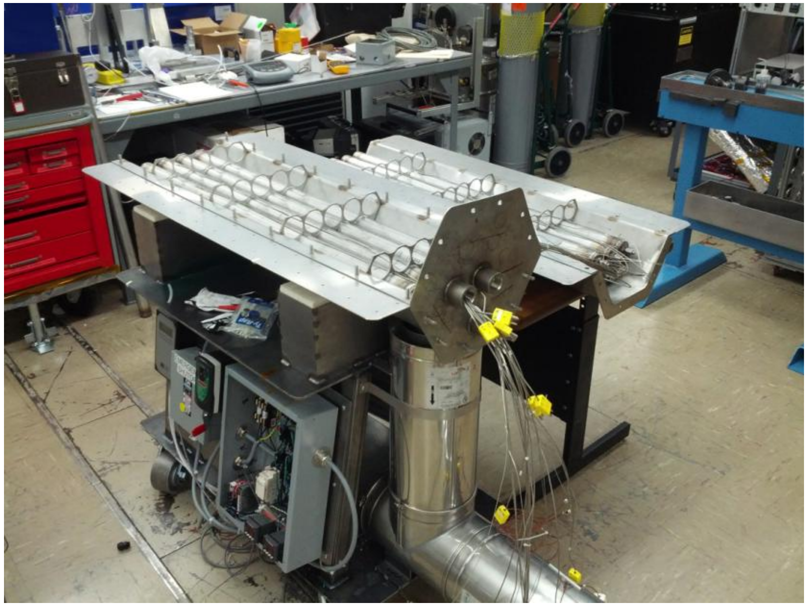
JPL

	6-hr storage	12-hr storage	18-hr storage	Notes
Net Power (MW_e)	103	103	103	Ref:
Gross Power (MW_e)	118	118	118	
Rankine effic.	37.4%	37.4%	37.4%	
Thermal storage (MWh_t)	1893	3786	5679	
Temp range (500-375 °C) for supercritical fluid	125	125	125	
Temp range (500-390 °C) for molten salt	110	110	110	Assumes same bypass ops.
Molten Salt (HiTec Solar Salt) T_1 - 500 °C/T_2 = 390 °C				
Cp salt (J/kg/K)	1550	1550	1550	
Mass Salt (10^6 kg)	52	104	156	includes 30% stagnant excess
Cost of salt ($M) (@ $2/kg)	104	208	312	
Cost of salt ($M) (@$8.80/kg)	457	915	1372	
Pumps+HEx ($M)	~~30~~	~~45~~	~~60~~	No pump, Hex in single tank
Tanks ($M)	~~43~~	~~64.5~~	~~86~~	Tank cost removed
Piping, Insulation, Valves, Fittings ($M)	1.5	1.5	1.5	
Foundation & Support Structures ($M)	0.5	0.75	1	x1.5 factor
Instrumentation & Control ($M)	6	6	6	
Total $M (@$2/kg)	112	216	320	Tank cost removed
Total $M (@$8.80/kg)	465	923	1380	Tank cost removed
Salt $/$kWh_t$ (@ $2/kg)	55	55	55	
Total $/$kWh_t$ (@ $2/kg)	59	57	56	
Salt $/$kWh_t$ (@$8.80/kg)	242	242	242	
Total $/$kWh_t$ (@8.80/kg)	246	244	243	
Supercritical Fluid (Naphthalene @ T_1=500°C/T_2=375°C, 880 psia)				
Fluid Cost ($/$kWh_t$)	2	2	2	Naphthalene ($0.33/kg bulk)
Tank material cost ($/$kWh_t$)	33	33	33	SS 316L ($1.40/kg bulk)
Total Fluid cost ($M)	3.8	7.6	11.4	
Tank Material cost ($M)	62	125	187	
Pumps + HEx ($M)	0.0	0.0	0.0	Internal HEx single tank
Piping, Insulation, Valves, Fittings ($M)	1.5	1.5	1.5	same as for salt
Foundation & Support Structures ($M)	0.5	0.75	1	same as for salt
Instrumentation & Control ($M)	6	6	6	same as for salt
Total $M	74	141	207	
Total $/$kWh_t$	39	37	36	

- Full analysis for comparing molten salt vs supercritical fluids for utility scale for 6-, 12- and 18-hr storage.
  - 100 MWe utility from report by Worley Parsons
- System cost using supercritical fluids is lower than molten salt
  - No external heat exchanger
  - No second pump (only HTF pump from field)

Current Activities at JPL

- Currently JPL is in process of
  - 5 kWh cycle testing completed – data analysis ongoing
  - Design of 10 kWh system initiated



5 kWh tank testbed

5 kWh tank tested at 500 ^{o}C

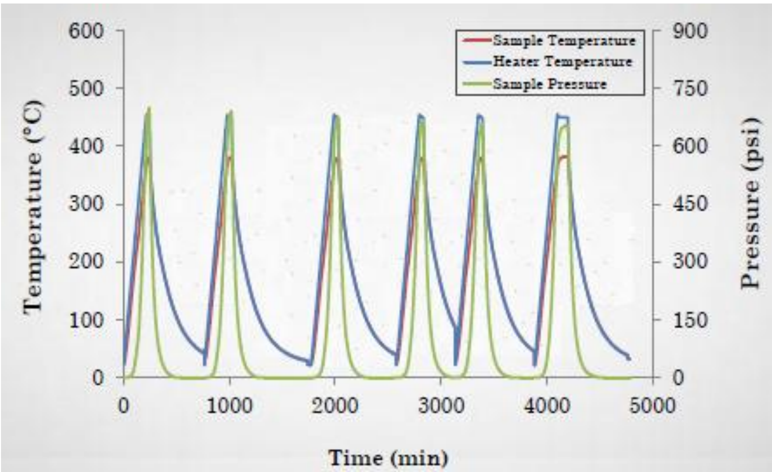
Current Activities at JPL

- Chromasun MCT panels procurement to be initiated shortly to test 10 kWh tank

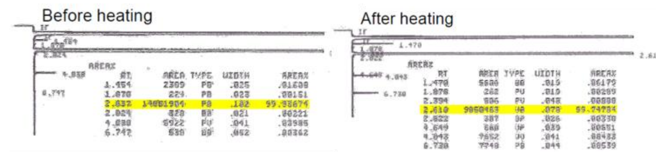
Chromasun solar panels as seen on Santa Clara Univ building rooftop.

Current Activities at UCLA

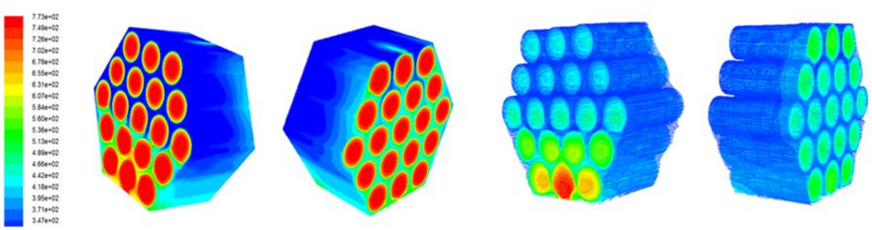
Thermal Testing of Fluids



Chemistry Evaluation



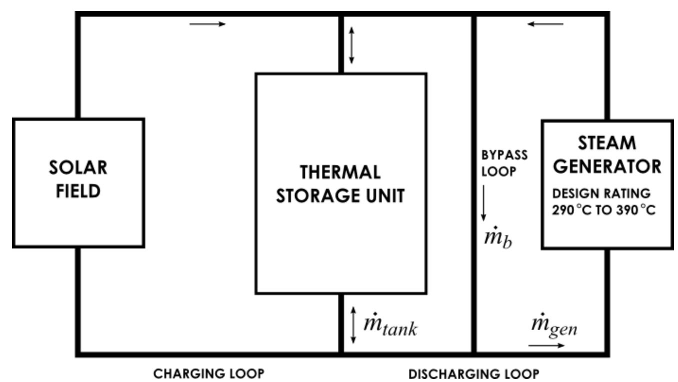
Heat and Mass Transfer



t = 4 min

t = 75 min

System Modeling



Summary

- A novel thermal energy storage concept has been funded for development by ARPA-E that promises significant cost advantages over molten salt system

- The cost of the chosen fluid is much lower than molten salt and the difference will continue to grow as demand for nitrates grow for use as fertilizer

- A robust program to develop alternate fluids is in the process of being developed for testing.
  - Results from the testing will be used for building larger-sized tanks as the processes get worked out